Engineering Systems Designs for a Recirculating Heavy Ion Induction Accelerator *

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Abstract

Recirculating heavy ion induction accelerators are being investigated as possible drivers for heavy ion fusion. Part of this investigation has included the generation of a conceptual design for a recirculator system. This paper will describe the overall engineering conceptual design of this recirculator, including discussions of the dipole magnet system, the superconducting quadrupole system and the beam acceleration system. Major engineering issues, evaluation of feasibility, and cost tradeoffs of the complete recirculator system will be presented and discussed.

I. INTRODUCTION

For the last several years, the U.S. effort to develop heavy ion drivers for inertial fusion has focussed on linear induction accelerators. [1] As part of this comprehensive effort, systems studies have been conducted to assess the cost and feasibility of heavy-ion induction linacs and to identify potential scenarios for reducing the size and cost of power-plant scale drivers. [2,3] An old idea for cost reduction that has not been aggressively investigated, is to use the linear induction accelerator technology in a recirculating configuration. The recirculating induction accelerator reuses the induction accelerating cells by bending the beam in a closed path. The amount of core material is reduced inversely as the number of beam recirculations resulting in a potential reduction of total system cost. This potential for cost reduction has motivated an extensive evaluation of recirculating heavy-ion induction accelerators for inertial fusion drivers by the Beam Research Program at Lawrence Livermore National Laboratory in cooperation with the HIFAR Program at Lawrence Berkeley Laboratory.

II. RECIRCULATOR DESCRIPTION

A recirculating induction accelerator can have many possible configurations to achieve specified output parameters. Typically, a recirculator will consist of multiple acceleration rings similar to the example shown in figure 1 for a 4 MJ heavy ion driver which accelerates four ion beams simultaneously in four rings. Multiple rings are used to limit the dynamic range over which the components in a single ring must operate.

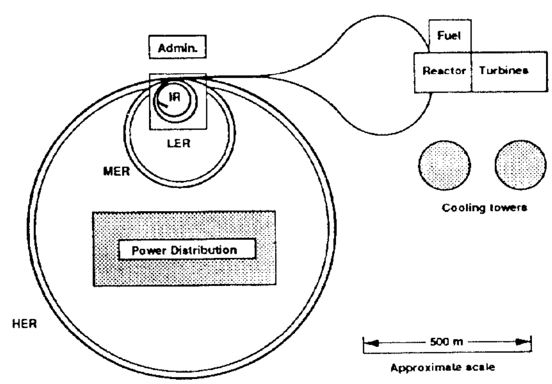

Figure 1. Example of a 4 MJ recirculator driver.

The beams are injected into the first recirculating ring at a low energy (2-3 MeV) where they get accelerated by making multiple passes through the induction accelerating cells. When the beams reach the maximum ring energy they are extracted from the ring by fast kicker magnets and injected into the next ring for additional acceleration. This scenario is repeated until the beams reach the final energy required at the target.

During acceleration, the ion beams must be compressed from an initial pulse duration of a few hundred microseconds to a pulse duration of a few hundred nanoseconds. The ion beams are then compressed to approximately ten nanoseconds in a drift compression section between the accelerator and the target. Pulse compression is achieved by inducing a velocity variation on the beams with the tail of the pulse being accelerated more than the head of the pulse.

Each accelerating ring is composed of three major components, the induction accelerating cells, quadrupole focussing magnets and dipole bending magnets. The configuration of a typical lattice section of the accelerator is shown in figure 2.

The accelerating systems provide the energy to accelerate the ion beam to the required energies. These systems consist of pulsed modulators that generate and deliver the accelerating potential to induction accelerating cells. In a recirculator system, these pulsed modulators must be capable of generating the accelerating potential every time the ion beam completes a lap around the recirculator. The time required for an ion beam to complete a lap varies from 100's of μs to 10's of μs in a

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single accelerating sequence depending on the exact configuration of

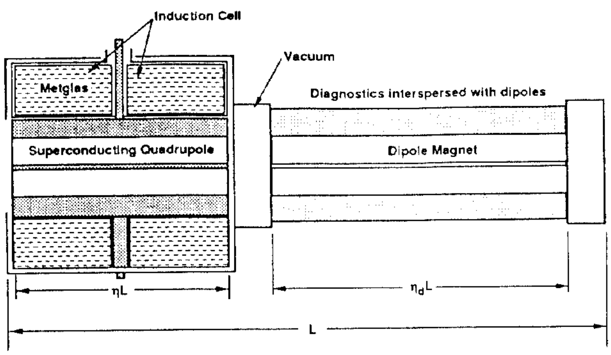

Figure 2. Typical half-lattice period section of a recirculator

the recirculator. In addition to the accelerating potential, each pulsed modulator must also generate a potential for resetting the induction core material between acceleration pulses. Feasible methods for generating the accelerating and reset potentials have been identified using mature technologies.[4] More advanced solid state technologies are also being investigated.

The quadrupole magnet system, which is necessary to transport the ion beam through the accelerator uses superconducting magnets. Superconducting magnets were chosen for the system studies because reasonable accelerator efficiencies were not possible with conventional quadrupole magnets. The superconducting quadrupoles are configured in an array of four magnets, one per beam. A critical parameter for the quadrupole magnets is the radial size of the array. Because the induction cell surrounds the quadrupole array, the array size affects the quantity of the magnetic material which impacts the cost and efficiency of the recirculator.

The dipole magnet system consists of dipole magnets and pulsers that generate a time varying magnetic field to bend the ion beam in a constant radius as the beam energy increases. Hundreds of megajoules of energy are required to generate the dipole magnetic fields. Greater than 90% of this dipole field energy must be recovered to achieve a reasonable driver efficiency (≥ 20%). This requires careful design of low-loss pulsed dipole magnets and the use of energy recovery schemes in the dipole pulser system. [5]

III. SYSTEM PROPERTIES

The systems associated with the three components, the induction cells, the dipole pulsers, and the quadrupole system are the three primary cost drivers in a recirculating accelerator. The parameters chosen for these three systems greatly impact the overall cost and efficiency of the recirculator. Based on estimates of the 4 MJ driver shown in figure 1, the accelerating system is the single largest cost component of the entire system. The accelerating system and the dipole magnet system account for most of the system losses so it is important to understand their impact on the overall system efficiency. The impact of the accelerating systems and the dipole systems will be discussed in the following sections.

A. Accelerating Systems

The cost of the accelerating system has two major components, the induction cells and the induction cell drivers. The primary cost component of the induction cell is the cost of the magnetic material in the cell which is directly proportional to the magnetic material volume. The volume of magnetic material necessary in the induction cells is dependent on the required cross-sectional area as well as the geometry of the recirculating ring. The cross-sectional area of the magnetic core material is proportional to the integral of the accelerating voltage as shown in equation 1, where ΔB is the flux density used in the magnetic material, PF is the packing fraction of the magnetic core, Δt is the pulse width, N_L is the number of laps used for acceleration, V_c is the acceleration potential, and A_m is the cross-sectional area.

$$A_m = \frac{1}{N_L \, \Delta B \, PF} \int_0^{\Delta t} V_c \, dt \qquad (1)$$

The volume of the magnetic material required is given by equation 2 where A_m is the magnetic core cross-sectional area as defined in equation 1, L is the length of the magnetic core material and r_i is the inner radius of the induction cell.

$$V = \pi A_m \left(\frac{A_m}{L} + 2r_i \right) \qquad (2)$$

The cost of the induction cell drivers scale with the beam current, final beam energy and induction cell losses. The losses in the induction accelerating system are primarily due to magnetic material losses in the induction cell. The volumetric losses in a Metglas ™ loaded induction cell can be expressed as shown in equation 3 where ΔB_m is the flux density used in the magnetic material, Δt is the pulse width, and K, m and n are constants that depend on the type of Metglas. For 2605 S-2, m≈-.8, n≈1.8 and K≈139.

$$\frac{E_m}{V} = K \, \Delta t^m \, \Delta B_m^n \qquad (3)$$

Equation 3 shows that the magnetic losses can be decreased by lowering the ΔB_m used in the induction core. This can be done by increasing the cross-sectional area of the induction core (see equation 1). However, the magnetic material losses cannot be decreased indefinitely by increasing the cross-sectional area. There is a point where the increasing core volume begins to increase total losses faster than the corresponding decrease in ΔB reduces losses. Fortunately the recirculator core configuration is in the range where increasing the cross-sectional area can significantly reduce core losses.

Figure 3 shows how the cost and power consumption of the 4 MJ recirculator design example shown in figure 1 varies as a function of excess magnetic core material. For this particular example, the power consumption, which includes all power that must be supplied to the recirculator, can be decreased by about 50% by using 500% excess core material in the induction cells. The cost on the other hand, which includes all system costs, increases less than 20%. The recirculator has more flexibility for reducing magnetic material losses with the addition of excess material than a linear induction accelerator.

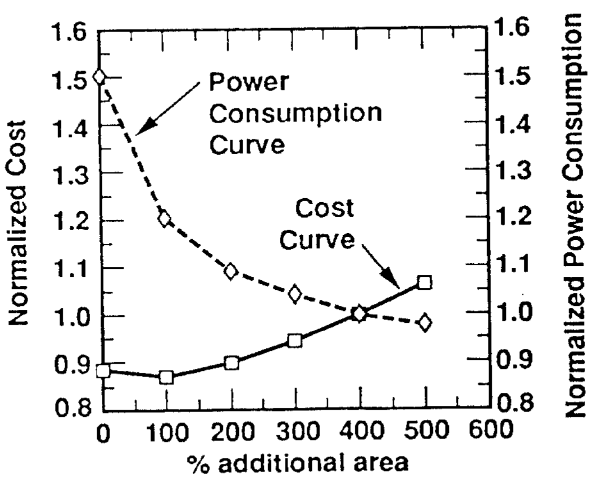

Figure 3. Cost and power consumption vs. additional magnetic material cross-sectional area.

B. Dipole System

The dipole magnet system is also composed of two major components, the dipole magnets and the dipole magnet pulsers. These costs however are relatively small compared to the cost of the accelerating systems. The dipole system has a much greater impact on the overall system efficiency than on the system cost. For this reason, only the energy relationships of the dipole system will be discussed.

A large amount of energy (>100 MJ) is required to generate the magnetic fields that bend the ion beam. A large percentage (>90%) of this energy must be recovered after each accelerating sequence in order to maintain a driver efficiency of greater than 20%. The dipole energy, E_d, is expressed by the relationship shown in equation 4 where B_d is the magnitude of the dipole field, A_c is the cross-section of the dipole field volume, μ_o is the permeability of free space and $[B\rho]$ is the particle rigidity. Equation 4 shows that the energy stored in the dipole magnetic

$$E_d = \frac{\pi B_d}{\mu_o} A_c [B\rho] \qquad (4)$$

field of a recirculating accelerator is linearly dependent on the magnitude of the dipole field. This is because an increase in the dipole field decreases the volume in which the field must be generated.

The impact of the magnitude of the dipole magnetic field is shown in figure 4. The power consumption curve shows the linear dependence explained by equation 4. The cost of the recirculator decreases as the dipole field increases because the cost of the quadrupole focussing system is approximately linearly dependent on the circumference of the recirculator. As the circumference decreases with increasing dipole field, the quadrupole system costs decrease. Figure 4 shows that for this particular example, a region of diminishing returns is reached for dipole fields greater than 1 T. In this region, the efficiency continues to decrease linearly while the decreases in system cost become smaller and smaller.

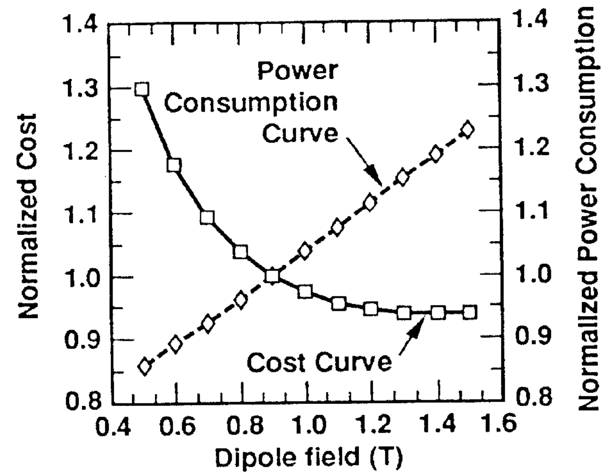

Figure 4. Cost and power consumption vs. dipole field strength.

IV. CONCLUSIONS

There are many more aspects of the recirculator systems that have been examined but space only permits the presentation of these few examples. Cost estimates of the complete system indicate that significant cost reductions by recirculation are possible. System studies have shown that in addition to lower driver cost (≤500 M$), there is considerable flexibility to make tradeoffs between system parameters in order to achieve an efficient (20 - 25%) and cost effective system.

V. REFERENCES

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